Design and Analysis of Robust SMES Controller for Stability Enhancement of Interconnected Power System Taking Coil Size Into Consideration

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***Abstract*—In power applications, efficiency and effectiveness of SMES with proper control are promising and highly remarkable, however, quite costly. Accordingly, optimum design and utilization are essentially needed. This paper presents the design and analysis of robust SMES controller for stability enhancement of interconnected power system taking coil size into consideration. With lead/lag controller structure, parameters of robust SMES controller can be optimized by a metaheuristic method; meanwhile, a multiplicative uncertainty is included in the design to cope with system uncertainties. Lastly, aiming at achieving optimum design and utilization, robust controllers for SMES with different coil sizes are examined to investigate performance and robustness under different situations via simulation studies.**

***Index Terms*—Metaheuristic method, power system stability, robust control, superconducting magnetic energy storage.**

I. Introduction

RECENT increase in wide area disturbances and complexity in managing power transactions have reduced considerably operational stability margins and have let to the need for stability enhancement of interconnected power systems. To keep reliable and stable operation, modern power systems rely inevitably on stabilizing devices [1]. Alternatively, superconducting magnetic energy storage (SMES) is among the choices. The SMES can be utilized as an effective device for serving such tasks, since it has the ability to swiftly exchange electrical energy with a power system. Today's advanced technology has practically encouraged the utilization and application of SMES systems in many power systems [2].

With proper control, SMES can be regarded as a promising solution for advancing power quality and enhancing power system stability. However, because of high investment of SMES systems, optimum design and utilization are essentially needed [3]. Moreover, different SMES coil sizes and controller parameters can significantly yield different performance and robustness when subjected to system disturbances [4], [5].

This paper presents the design and analysis of robust SMES controller for stability enhancement of interconnected power system. Different SMES coil sizes in terms of inductively stored energy are considered for analysis of performance and robustness. SMES model with simultaneous active and reactive power control scheme including a characteristic of SMES coil current is employed for realizing a permissible range of SMES operation. The lead/lag structure is employed for a controller and the design of robust SMES controller (RSMES) is achieved by a metaheuristic method, i.e., hybrid tabu search and evolutionary programming (Hybrid TS/EP); meanwhile, a multiplicative uncertainty model is also considered to cope with system uncertainties. Experimentally, simulation studies are carried out under different situations in order to achieve optimum design and utilization.

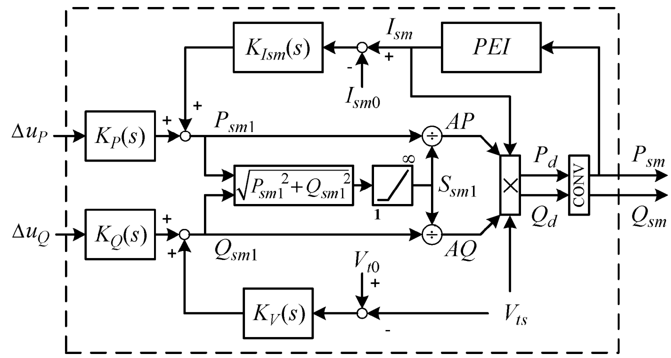

Fig. 1. SMES Control Scheme.

II. SMES Controller Design

A. SMES Control Scheme

The SMES control scheme, as depicted in Fig. 1, is used [6]. It is a simultaneous active and reactive power control scheme, which includes three controllers of $K_P(s)$, $K_Q(s)$ and $K_{Ism}(s)$, where, $K_P(s)$ and $K_Q(s)$ are the SMES active and reactive power controllers, respectively, and, $K_{Ism}(s)$ is the SMES coil current controller. In particular, the effect of SMES coil current (I_{sm}) is considered, since the dynamic behavior of I_{sm} significantly affects the overall performance of SMES. In practice, I_{sm} is not allowed to reach zero to prevent the possibility of discontinuous conduction under unexpected disturbances. On the other hand, high I_{sm}, which is above the

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maximum allowable limit, may lead to loss of superconducting properties. Based on the hardware operational constraints, the lower and upper coil current limits are considered and assigned as $0.30I_{sm0}$ and $1.38I_{sm0}$, respectively [4], where, I_{sm0} is an initial value of I_{sm}.

The *PEI*block in Fig. 1 determines the present I_{sm} based on P_{sm}. In particular, I_{sm} can be calculated by (1) and (2) as follows,

$$Eout = \int P_{sm} dt \cdot S_{sm,base}, \tag{1}$$

$$I_{sm} = \sqrt{I_{sm0}^2 - 2E_{out} / \left(L_{sm} \cdot I_{sm,base}^2\right)}, \tag{2}$$

where, L_{sm} is the SMES coil inductance, (H); E_{out} is the SMES energy output, (J); $I_{sm,base}$ is the SMES current base, (A); and $S_{sm,base}$ is the SMES MVAbase, (MVA). Subsequently, the energy stored in the SMES unit (E_{sm}) and the initial E_{sm} (E_{sm0}) can be determined by (3) and (4) as follows,

$$E_{sm} = E_{sm0} - E_{out}, \tag{3}$$

$$E_{sm0} = 0.5 L_{sm} I_{sm0}^2 \cdot I_{sm,base}^2, \tag{4}$$

The desired SMES output active and reactive power (P_d and Q_d) can be expressed as

$$P_d = V_{ts} I_{sm} AP, \tag{5}$$

$$Q_d = V_{ts} I_{sm} AQ, \tag{6}$$

where, AP and AQ are the active and reactive power fractions, respectively. For simplicity, V_{ts} is a steady state bus voltage of SMES unit, (pu). The SMES output active and reactive power, i.e., P_{sm} and Q_{sm} are the output of the SMES controlled converter (CONV), which is represented by a first order time-lag compensator as follows,

$$P_{sm} = 1/(1 + 0.01s) P_d, \tag{7}$$

$$Q_{sm} = 1/(1 + 0.01s) Q_d. \tag{8}$$

In this paper, it is assumed that for a nominal condition the SMES unit should not supply/receive active and reactive power to/from the power system. On the other hand, the SMES unit should alleviate power system oscillations when subjected to system disturbances.

B. Robust Controller Design

To enhance the power system stabilization, the structure of 2nd order lead/lag compensator is used in the design of $K_P(s)$ and $K_Q(s)$ controllers as

$$\Delta u_{CTL} = K_C \frac{sT_W}{1 + sT_W} \left[\frac{1 + sT_1}{1 + sT_2}\right] \left[\frac{1 + sT_3}{1 + sT_4}\right] \cdot \Delta u_{IN}, \tag{9}$$

where, Δu_{CTL} is the control output signal of controller; Δu_{IN} is the feedback input signal of controller; K_C is a controller gain; T_W is a wash-out time constant (s); and, T_1, T_2, T_3 and T_4 are time constants (s). Note that Δu_{IN} for $K_P(s)$ is the tie-line active power deviation (ΔP_{tie}), and Δu_{IN} for $K_Q(s)$ is the tie-line reactive power deviation (ΔQ_{tie}).

In this paper, T_W is set to 10 s. The control parameters K_C, T_1, T_2, T_3 and T_4 are optimized using Hybrid TS/EP [5] based on the following objective function F,

$$\begin{aligned} \text{Min} \quad & F(K_C, T_i) = \varphi + \gamma, \\ \text{st.} \quad & K_{\min} \le K_C \le K_{\max}, \\ & T_{\min} \le T_i \le T_{\max}, \quad i = 1, \ldots, 4 \end{aligned} \tag{10}$$

where, $K_{\min}, K_{\max}, T_{\min}$ and $T_{\max}$ are the minimum and maximum values of a controller gain and a time constant, respectively. φ is the difference between the actual and the desired damping ratios of the dominant power oscillation mode. γ is the normalized robustness index in terms of a multiplicative stability margin (MSM). It should be noted that the larger the MSM, the better the robust stability margin will be.

III. SMES Coil Size Analysis

In general, with proper control, SMES with sufficiently large stored energy and rating capacity can provide satisfactory effective performance. However, SMES coil, as a heart of SMES, is costly. SMES with smaller coil size, which is not losing much effective performance, is always preferred. With robust controller design mentioned in previous section, this section provides the analysis criterion and analysis procedure aiming at achieving optimum design and utilization of SMES.

A. Analysis Criterion

For analysis purpose, SMES with controller in a power system is examined under two different situations, i.e., *normal* and *heavy* load operating conditions. In addition, two fault conditions, i.e. *near* and *far* SMES locations, are employed in order to evaluate the stability level of a power system. In particular, a 3-ϕ fault to ground is applied with fault duration of 50 ms.

Since, there is a relationship between SMES coil size (L) and level of power system stability, $L - K$ relationship can be obtained by observing power angle deviation $(\Delta\delta)$ when subjected to fault conditions and K can be calculated by (11) as

$$K = \frac{\int \Delta\delta^2 dt}{\int \Delta\delta^2_{(L=10\ \mathrm{H})} dt}, \tag{11}$$

where, K is a stability index. In this paper, SMES with a coil size $L = 10\ \mathrm{H}$ [5] is used as a benchmark.

B. Analysis Procedure

The following analysis procedure is applied to the case of a single machine infinite bus (SMIB) power system. The details of power system and SMES specifications are in [5]. However, with the same concept, it can also be applied to other interconnected power systems. The analysis procedure can be described as follows.

Step 1) Set an initial SMES coil current, e.g. $I_{sm0} = 1.9\,\mathrm{kA}$.

Step 2) Set a power system to heavy load condition.

Step 3) For $L = 1 \sim 10\ \mathrm{H}$, search for controller parameters by using the design method in Section II-B.

Step 4) Perform fault simulation test based on two fault conditions.

TABLE I
SMES CONTROLLER PARAMETERS

L(H)	P-Controller			Q-Controller		
	K_C	T_1(s)	T_2(s)	K_C	T_1(s)	T_2(s)
10	5.80	0.00944	0.0312	0.0904	0.0110	0.0281
9	6.55	0.0100	0.0300	0.0803	0.0108	0.0242
8	7.47	0.00965	0.0289	0.114	0.0115	0.0307
7	8.70	0.0116	0.0273	0.101	0.00980	0.0277
6	10.3	0.0113	0.0354	0.114	0.00831	0.0319
5	12.5	0.0107	0.0353	0.0848	0.0116	0.0320
4	16.0	0.0117	0.0291	0.117	0.0109	0.0342
3	21.7	0.00846	0.0260	0.0980	0.0103	0.0253
2	33.1	0.0100	0.0303	0.0829	0.00876	0.0241
1	67.8	0.00846	0.0260	0.0980	0.0103	0.0253

Step 5) Evaluate $L-K$ relationship from all SMES coil sizes.
Step 6) Similarly, evaluate $L-K$ relationship based on normal operating condition.
Step 7) Determine minimum SMES coil size.
Step 8) Vary initial SMES coil current, e.g. $I_{sm0} = 2.9$ kA, 3.9 kA, and repeat Step2 ~ Step7.
Step 9) Determine combination of initial SMES coil current and minimum coil size.

It should be noted that an initial SMES coil current to be selected for analysis may involve many concerns and aspects, and it depends on experiences of the designer.

C. Some Simulation Results

The simulation studies are carried out based on MATLAB programming for robust controller design. For time domain simulation, fault conditions are examined based on Dymola with ObjectStab [7]. Following analysis procedure, some simulation results can be obtained for further analysis towards optimum design and utilization of SMES. For SMIB case, the desired damping ratio (ζ_{des}) is set to 10% for the design of RSMES for all SMES coil sizes. Table I shows controller parameters for each coil size.

Experimentally, time domain simulations are also performed to examine and investigate performance and robustness of RSMES. Fig. 2 shows some comparison results for cases of no-control, $L = 10$ H, $L = 5$ H (with re-design controller), and $L = 5$ H (without re-design controller). It is clearly that with properly designed controller SMES can appropriately perform with satisfactory performance, even though the SMES coil size is reduced. However, the SMES coil size should be carefully minimized to avoid deterioration of effective performance when subjected to disturbances.

To determine a suitable SMES coil size, the $L-K$ relationship is observed. Independent of the coil shape, Fig. 3 shows the $L-K$ relationship for heavy load conditions of SMIB case. From benchmark ($L = 10$ H), SMES coil size can be minimized to $L = 5$ H before suffering from effective performance degradation. Figs. 4–7 show some simulation results that reveal the deterioration of SMES effective performance due to limitations of stored energy capacity available for charge and discharge, and nonlinear effects of SMES coil current when approach upper/lower limits.

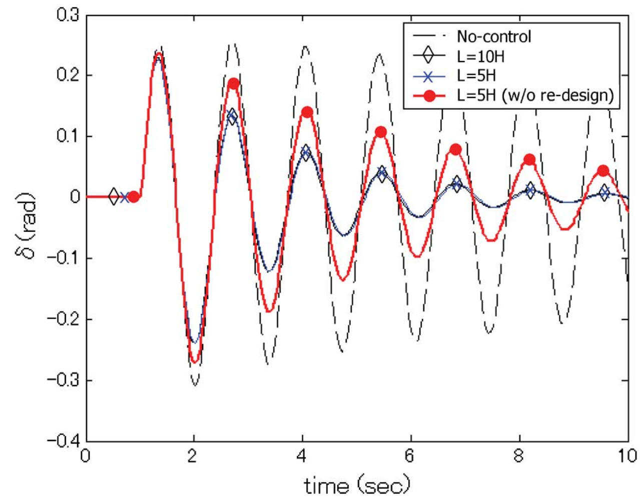

Fig. 2. Comparison of SMES effective performance (power angle δ).

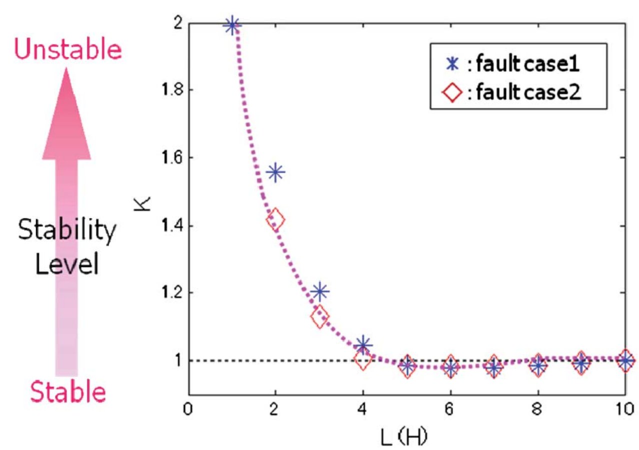

Fig. 3. $L-K$ relationship for heavy load conditions.

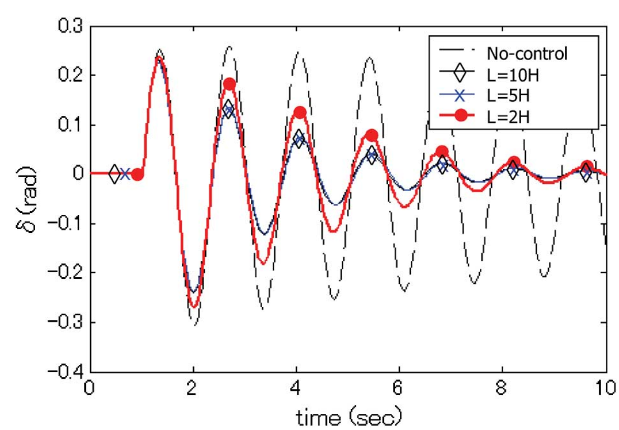

Fig. 4. Deterioration of SMES effective performance (Power angle δ).

In addition, it is worth to find the suitable combination of initial coil current and minimum coil size that fit best with a specific SMES application. As given in Table II, for SMIB case, all combinations have the best stability index for their corresponding initial currents.

D. SMES Modular Application

To develop a SMES system for a specific application, it could be technically and practically difficult and require plenty of researches and experiences, especially for large-scale power

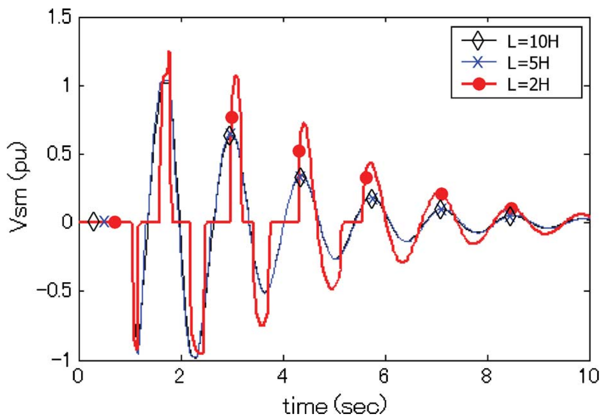

Fig. 5. SMES coil voltage V_{sm} due to stored energy capacity.

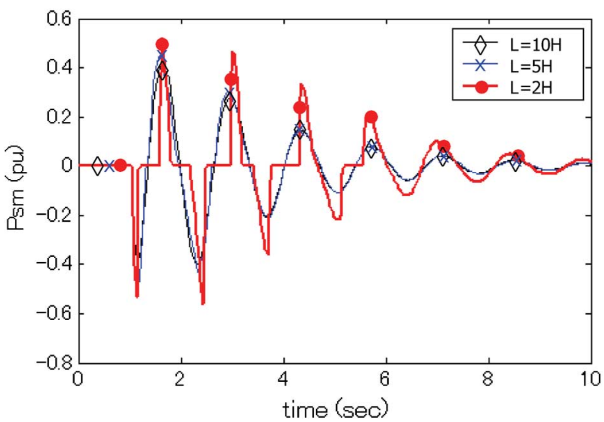

Fig. 6. SMES output P_{sm} due to stored energy capacity.

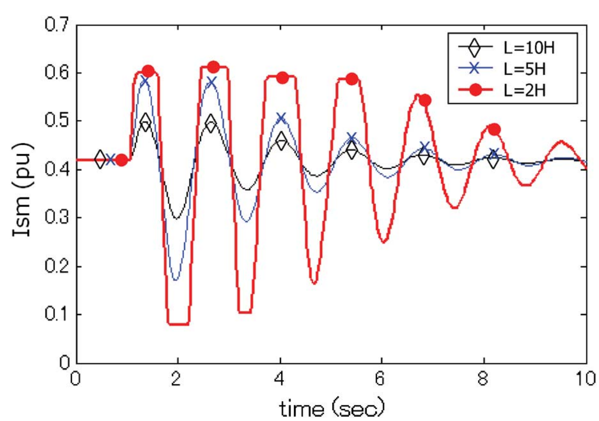

Fig. 7. SMES coil current I_{sm} due to stored energy capacity.

applications. Moreover, it could be apparently expensive and time-consuming [8]. To alleviate and overcome such difficulty, SMES modular application could be employed. The concept of SMES modular application as shown in Fig. 8 is taking advantage of modular design of compact SMES unit. Commercially, it is better to manufacture SMES units as mass production to reduce overall cost, including development and construction costs, and time to market. Meanwhile, this would make SMES feasible for other applications in general.

IV. Conclusions

This paper presents the design and analysis of robust SMES controller for stability enhancement of interconnected power system. Different SMES coil sizes in terms of inductively stored energy are considered for analysis of performance and robustness. With lead/lag controller structure, parameters of robust SMES controller can be optimized by a metaheuristic method, which reduces design efforts. Meanwhile, a multiplicative uncertainty included in the design copes with system uncertainties and improve robust performance of designed SMES controller when faces with stored energy capacity constraints and coil current limits. Experimentally, simulation studies reveal that the optimum design and utilization of SMES can be achieved with appropriate solution by examining and investigating simulation results based on the proposed analysis procedure.

TABLE II
Combination of Initial Coil Current and Minimum Coil Size

	I_{sm0}=1.9kA	I_{sm0}=2.9kA	I_{sm0}=3.9kA
Minimum SMES Coil Size (H)	5H	2H	1.5H

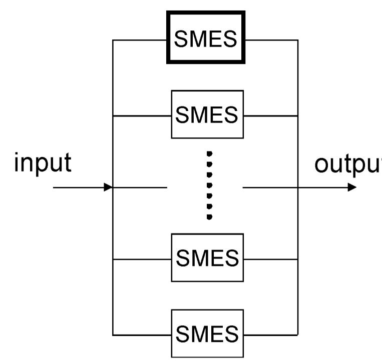

Fig. 8. Concept of SMES modular application.

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